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THE MEASUREMENT OF VISCOSITY AND A NEW FORM OF VISCOSIMETER

BY

H. C. HAYES

AND

G. W. LEWIS



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THE MEASUREMENT OF VISCOSITY AND A NEW FORM OF VISCOSIMETER

BY H. C. HAYES and G. W. LEWIS

ABSTRACT OF PAPER

This paper deals with the measurement of viscosity. It predicts the errors which are introduced by the various types of viscosimeters and verifies these predictions in case of the short capillary types such as the Saybolt, Engler, and Redwood and the orifice types such as the Carpenter, by comparing the temperature vs. viscosity curve for a light and a medium lubricating oil, as given by these meters, with the true curves as determined by a modified form of Poiseuille's capillary tube method.

The work shows that the short capillary types give results about 50 per cent too small and the orifice types give results about 100 per cent too small, and further, that none of these meters give accurate comparative results for two different oils or for the same oil at different temperatures.

The only type of viscosimeter on the market that can be expected to give accurate results on theoretical grounds is the Stormer. This instrument attempts to measure the viscosity in terms of the torque required to spin a disk within the liquid, but the mechanical difficulties met with are such as to debar this type.

The authors have designed and thoroughly tested out a viscosimeter which embodies all the good points of the Stormer and none of its defects. They measure the viscosity in terms of the torque which a cylinder experiences when suspended within a rotating liquid. This method eliminates all error due to friction. The results given by this meter agree with the true curves for the light and medium oils to within 1 per cent and can safely be used as a standard.

The advantages of this viscosimeter are evident. The instrument can be calibrated to give direct readings of the viscosity; the oil is not handled during a complete test at various temperatures; the design of the instrument is such that the temperature of the specimen follows closely the temperature of the bath, so the data for the temperature vs. viscosity curve can be taken while the sample is cooling; the meter gives the viscosity of mixtures, such as paints, as well as for liquids that have been carefully filtered; there are no glass parts to break; the personal error is eliminated and the meter can be made self recording.

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THE MEASUREMENT OF VISCOSITY AND A NEW FORM OF VISCOSIMETER

By

H. C. HAYES,¹ SWARTHMORE, PA.

and

G. W. LEWIS,² SWARTHMORE, PA.

Non-members

In determining the lubricating properties of an oil, the viscosity test is considered of great value, since by means of this test a good oil can readily be distinguished from a poor one. It is therefore very important that the engineer be able to measure the viscosity of an oil and also the variation of viscosity with temperature.

2 The present paper, dealing with the measurement of viscosity, gives in part the results of a somewhat extended research on the lubricating properties of oils. It is to be followed by a paper giving the relation between the lubricating properties of oils and various easily measurable physical properties.

VISCOSITY

3 Matter in all states exhibits a gradual yielding to tangential forces which tend to change its form. This property is termed viscosity and may be defined quantitatively as the tangential force per unit area divided by the shear per unit time.

4 To gain a clear physical concept of this definition, consider a plane surface, Fig. 1, of area S , parallel to and at a distance d from another large plane surface, and the intervening space filled with a liquid whose coefficient of viscosity is η . If a given force, F , acting on this plane, is applied to S , the surface will be dragged along and

¹ Prof. of Physics, Swarthmore College.

² Asst. Prof. of Engrg., Swarthmore College.

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will finally attain a steady velocity, which denote by V . In accordance with the above definition, the relation between these various factors would then be

$$\eta = F/S \div V/d \text{ or } \eta = F \cdot d \div S \cdot V \dots \dots \dots [1]$$

the value of η depending on the units in which these various factors are measured. If absolute values are desired, the factors on the right hand side of the equation are to be measured in C.G.S. units; but if relative values will suffice, as is the case in nearly all engineering work, they may be measured in any units.

5 It must be borne in mind that equation [1] is not true when the velocity, V , is changing, for then only a part of the force, F , is used to overcome viscosity, a part being used in giving accelerated



FIG. 1 CONCEPTION OF VISCOSITY

motion. Under such conditions, another term must be added to this equation. The nature of this term is not difficult to see, for let equation [1] be written $F = \eta \cdot S \cdot V/d$. When there is accelerated motion, the force, F , will be divided into two parts, the part used to overcome viscosity and that used to give accelerated motion. Call these parts f_1 and f_2 respectively, then at any instant $F = f_1 + f_2$, where $f_1 = \eta \cdot S \cdot V/d$ and $f_2 = M \cdot dV/dt$, where M is the mass that is being accelerated and dV/dt is the average change of velocity per second of this mass. The complete instantaneous equation thus becomes

$$F = \eta \cdot SV/d + M \cdot dV/dt \dots \dots \dots [2]$$

and the viscosity cannot be found from this equation unless the last term can be evaluated, which is usually difficult and often impossible.

DEVELOPMENT OF A WORKING FORMULA

6 In most physical measurements, comparative values are more easily obtained than absolute values. As a result measurements are made in terms of some standard, the absolute value of which has been determined by a more or less laborious process. In making measurements of viscosity, the standard usually chosen is water at a temperature of 20 deg. cent.

7 Girard and Poiseuille, by studying the flow of liquids through capillary tubes, were the first to measure the absolute value of viscosity with anything like accuracy. On the basis of his excellent experimental work on the viscosity of water, Poiseuille deduced the formula

$$V = K \cdot D^4 \cdot H/L$$

where V = volume of liquid transpired

L = length of capillary

D = diameter of capillary

H = pressure

K = constant for each liquid at a given temperature.

Later, this empirical formula and its corrections were proved by several investigators.¹

8 By assuming there is no slip at the surface of the capillary, that the liquid flows steadily without eddies or turbulent motion, and that there is no kinetic energy of efflux, then the transpiration formula for a liquid flowing under its own head becomes

$$\eta = \frac{\pi}{8} (hgr^4/lv) \rho t$$

where η = coefficient of viscosity (often contracted to viscosity)

h = liquid head

g = acceleration of gravity

r = radius of capillary

l = length of capillary

v = volume of flow

t = time of flow

ρ = density of liquid.

Experiment shows that the first assumption is true if the liquid is one that wets the surface of the capillary. The work of Reynolds shows the second assumption is true if the velocity of the liquid through the capillary is kept less than $700 \cdot \eta/\rho \cdot r$ cm. per sec. The third assumption, of course, can never be true. The liquid

¹ Stokes, Trans. Camb. Phil. Soc., 1849, vol. 8, p. 287; Wiedmann, Poggendorf's Annalen, vol. 99, p. 177; Hagenback, Pogg. Ann., vol. 109, p. 385; Stefan, Wien. Bar., vol. 46, p. 495; Couette, Ann. Chim. Phys., vol. 21, p. 433; Neumann, Vorträge über Hydrodynamik; Wilberforce, Phil. Mag., vol. 31, p. 407; Jacobson, Arch. f. Anat. u. Physiol. 1860, p. 80; Knibbs, J. Roy. Soc. N.S.W., vol. 29, p. 77; Boussinesq, Compt. Rend., vol. 110, p. 1160; Brillouin, La Viscosité (Gauthier Villars, 1907).

must have kinetic energy when it leaves the capillary. In accordance with equation [2], a correction term must be added which, according to Couette, Finkener, and Wilberforce, should be $-v\rho/8\pi lt$. The complete expression for the viscosity is therefore of the form

$$\eta = \rho (A \cdot t - B/l)$$

where A and B are constants for any piece of apparatus, ρ and t are the density and time of flow, respectively.

9 After a thorough examination of the recorded data on the viscosity of water, Knibbs concluded that the correct formula should be

$$\eta = \pi h g r^4 \rho t / 8 l v - 1.12 v \rho / 8 \pi l t$$

It is to be noted that the correction term is larger than that given by Couette. Moreover, this correction term varies with the time of flow, approaching zero when the velocity of flow is very slow, in which case t becomes very great. The value of the term increases with the temperature of the liquid since the time of flow decreases, and so the percentage of error in a viscosity vs. temperature curve due to neglecting this correction factor will increase abnormally toward the higher temperatures. This is due to two causes, the correction to be applied increases with the temperature and the value of the quantity to be corrected decreases rapidly with the temperature. Attention will be called to this fact when some of the various comparative methods are discussed. It is further to be noted that this correction term varies inversely as the length of the capillary. A short capillary requires a large correction term.

10 This formula, as corrected by Knibbs has been submitted to careful experimental test by Hosking, and by Bingham and White. These investigators have determined the constants of the formula experimentally and have obtained fair agreement with theory. The capillary tube method, as employed by these experimenters, though complicated and laborious, can be depended upon for giving absolute values of the viscosity, and the accuracy of any viscosimeter can be determined by a comparison with the results obtained by this method.

CLASSIFICATION OF VISCOSIMETERS

11 *Class 1. Short Capillary.* In meters of this type, the liquid to be tested is forced either by gravity or by pressure through the capillary and the viscosity is determined in terms of the time re-

quired for a given volume to pass through the meter, as compared with the time required for a standard liquid to discharge the same volume.

12 A cross section of a meter of this type is shown in Fig. 2. The essential parts of the instrument are a cylindrical bowl, *A*, in which the oil is placed and a short capillary tube *B*, through which it is discharged. The instrument must have temperature controlling and measuring devices, means for starting and stopping the flow and volume and time measuring apparatus.

13 To this class belong the Saybolt meter, adopted as a standard by the Standard Oil Co.; the Engler meter, adopted as a standard by the U. S. Government and Germany; the Redwood meter,

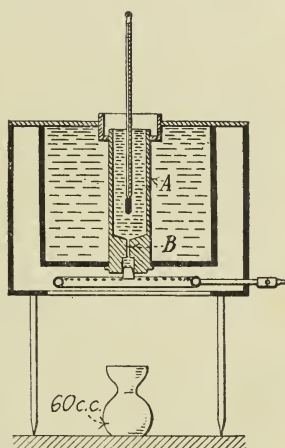


FIG. 2 SHORT CAPILLARY TYPE VISCOSIMETER

adopted as a standard in England; the Scott meter; and the pipette, adopted as a standard by the Pennsylvania Railroad and much used by chemists. The majority of the viscosimeters on the market are of the short capillary type.

14 *Class 2. Orifice.* This type employs an orifice in place of the short capillary of the previous type. Fig. 3 is a section of such a meter, in the cylindrical bowl, *A*, of which the oil to be tested is kept at constant head above the orifice, *B*. The Carpenter meter belongs to this class.

15 *Class 3. Dropping a solid body through a tube filled with the liquid,* the solid body being usually a sphere or a plunger. Meters employing this principle determine the viscosity in terms of the

time required for the body to drop a certain distance through the liquid, as compared with the time required for the same body to drop through a standard liquid. To this class of meters belong the Perkins meter which employs a plunger and vertical tube, and the

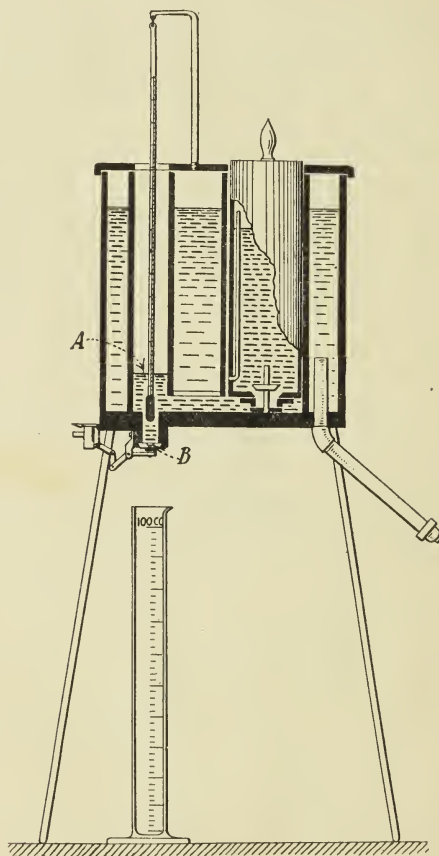


FIG. 3 ORIFICE TYPE VISCOSIMETER

Flowers meter which employs a small steel sphere and a slanting tube.

16 *Class 4. Oscillating Disk or Cylinder.* These meters determine the viscosity in terms of the damping which the oscillating disk or cylinder experiences when placed in the liquid as compared with the damping when placed in the standard liquid. The Doolittle meter is an example of this class.

17 *Class 5. Rotating Disk or Cylinder.* This type determines the viscosity in terms of the speed of rotation of the disk or cylinder in the liquid under test as compared with the speed of rotation in the standard, the driving torque remaining constant. The Stormer meter is an example of this class.

DISCUSSION OF THE VARIOUS TYPES

18 The value of each of the above types, so far as accuracy is concerned, can be estimated by noting whether they operate in accordance with equation [1] or [2], but before speaking of the various types it should be noted that only equation [1] will give accurate comparative results.

19 Write this equation in the forms

$$\eta_x = F_x \cdot d_x / S_x \cdot V_x$$

where the subscript x refers to the substance and conditions met with in connection with the liquid to be tested, and

$$\eta_s = F_s \cdot d_s / S_s \cdot V_s$$

where the subscript s refers in a similar manner to the standard liquid. Solving these two equations for η gives

$$\eta_x = \eta_s \cdot S_s \cdot V_s \cdot F_x \cdot d_x / F_s \cdot d_s \cdot S_x \cdot V_x$$

an expression which simplifies to

$$\eta_x = \eta_s (V_s / V_x) (F_x / F_s)$$

if the same apparatus is used in both cases, whereas if we apply the same operation to equation [2] we get

$$\eta_x = \eta_s [F_x - M_x \cdot dV_x / dt_x] / (F_s - M_s \cdot dV_s / dt_s) V_s / V_x$$

20 This expression cannot be simplified, for the expression within the brackets can never be made equal to unity. Moreover this expression is not constant, but varies with every liquid which is compared with the standard and with every change of temperature. It is therefore impossible to assign an accurate correction factor to an instrument which seeks comparative results if the instrument operates in accordance with equation [2], or, in other words, if there is any accelerated motion of the liquid during the testing operation.

21 In practice, the time, t , required for a definite volume of liquid to pass through the meter is measured instead of the velocity, V , and, if the force driving the liquid is gravity, the force F is easily

evaluated as $\rho \cdot h$, where ρ is the density and h the average head. Equations [1] and [2], in practice, thus become

$$\eta_x = \eta_s \cdot t_x \cdot t_s \cdot \rho_x \cdot \bar{h} / t_s \cdot \rho_s \cdot \bar{h} \quad \text{or} \quad \frac{\eta_x}{\eta_s} = \frac{\rho_x \cdot t_x}{\rho_s \cdot t_s} \dots \dots [1a]$$

$$\eta_x = \eta_s \cdot t_x / t_s [\rho_x \cdot \bar{h} - (M_x \cdot dV_x / dt_x) / (\rho_s \cdot \bar{h} - M_s \cdot dV_s / dt_s)] \dots [2a]$$

THE ACCELERATION ERROR

22 It is obvious that equation [2a] applies to all meters coming under *Classes* 1 and 2 since the liquid starts from rest in the meter chamber and leaves with a certain velocity and must therefore experience acceleration. In all these meters on the market the acceleration term ($M \cdot dV/dt$) is neglected since its evaluation is impossible and the formula then becomes identical with equation [1a]. An error which we shall call the acceleration error is thereby introduced.

23 The nature of this error can be predicted from an inspection of equation [2a]. The liquid having the smaller viscosity will pass through the meter with the greater velocity and the correction term ($M \cdot dV/dt$) will be larger in proportion for this than for the more viscous liquid. If, therefore, water is chosen as a standard in determining the viscosity of lubricating oil or any liquid which is more viscous than itself, the value $[(F - M \cdot dV/dt)/(F - M \cdot dV/dt)]$ will be larger than the value F/F and the value η as computed from the approximate formula [1a] will be too small. If, however, the liquid under test has a smaller viscosity than the standard the bracketed term will have a smaller value than F/F and the result as given by the approximate formula will be too large.

24 In the case of meters employing capillary flow, it is evident that the acceleration term will increase with the diameter of the capillary and decrease with its length and, as a result, we shall expect all meters using short capillaries to be subject to large error. Moreover, if we regard the orifice as a very short capillary, we should expect the error introduced in this type of meter to be still greater. The experimental results presented later prove these predictions to be correct.

SURFACE TENSION ERROR

25 Another error introduced in all the flow type viscosimeters, of both the capillary and orifice forms, is due to difference in the surface tension of the standard liquid and the liquid under

test. This error is prominent for those meters which discharge from the capillary or orifice into the air. As soon as the stream leaves the meter the film which forms on the free surface tends to contract, and thus decreases the cross section of the stream and retards the discharge. This contraction is greater for a liquid of high than for one of low surface tension. If water is used as the standard, since its surface tension is greater than for oils the flow of water will be retarded more than the flow for oils. The time of flow, t_s , will be increased in greater proportion than t_x , thus giving the ratio t_x/t_s , too small and the error will cause the value η_x to be too small. For oils and most liquids, the surface tension error and the acceleration error are additive.

26 This surface tension effect is, of course, negligible for a stream having high velocity, as the inertia of the moving mass prevents distortion of the stream lines. For the low velocities of efflux given by flow type viscosimeters, however, the effect is very noticeable, as can be seen by measuring the diameter of the efflux for two liquids of different surface tension. When conditions are most favorable for reducing the acceleration, namely velocity of efflux very small, they are most favorable for introducing the surface tension error.

CRITICAL VELOCITY ERROR

27 Another source of error in most capillary and orifice forms of viscosimeters is that the dimensions of the instrument are such that for the standard — water — the flow exceeds the critical velocity and the resulting turbulent flow makes the value of t abnormally large. This introduces an error, which also adds itself to the acceleration and surface tension errors. This fact was discovered during the research work about to be recorded but has, in the meantime been noted and investigated by Upton who found the error so introduced by the Engler viscosimeter to be great.

28 The three errors — acceleration, surface tension and critical velocity — are prominent in all the meters named above as standards and we should expect the viscosity as given by these meters to be in general much too low. The experimental results will show that it is.

29 Those meters based on the principle of dropping a solid body through a tube filled with the liquid to be tested should be more accurate than the capillary or orifice forms as they are free from the surface tension error and usually from the critical velocity

error. All are, however, subject to the acceleration error. All the liquid displaced by the falling body suffers acceleration. These meters are all of the flow type and may be regarded as of the short capillary form, the reduced section at the point where the falling body is passing being the capillary. The liquid flows across this section as truly as it does through the orifice or capillary.

30 The relation between the damping which an oscillating disk or cylinder experiences and the viscosity of the liquid in which it is immersed is complicated, and indeed the true relation is not known. Meters based on this principle, such as the Doolittle meter, do not give accurate results. They are nearly free from the surface tension and critical velocity errors, however, and though somewhat slow and difficult to operate, they give better results than the majority of flow types.

31 The constant speed of rotation which a disk or cylinder immersed in a liquid will attain under the action of a constant torque is a true measure of the viscosity of the liquid. The Stormer viscosimeter attempts to operate in accordance with this principle, but the friction of the moving parts is necessarily such that a constant torque cannot be obtained. With proper refinement, this meter could be made to give good results. The fact that a meter based on this principle can theoretically give accurate results has led to the development of a new viscosimeter now to be described.

THE NEW VISCOSIMETER

32 This viscosimeter operates in accordance with the principle that a solid body having a surface of revolution experiences, when suspended in a rotating liquid, a torque which is proportional to the viscosity of the liquid. The instrument is shown diagrammatically in Fig. 4. The specimen, *S*, is contained within a cylindrical chamber which is caused to rotate uniformly by a motor, *M*, through a worm drive, *R*. A cylinder, *C*, is suspended within the specimen by a thin steel wire, *W*, so that the axis of the rotating liquid coincides with the axis of the cylinder. The specimen chamber is provided with a cap, *V*, so shaped that the excess liquid can overflow when the cap is seated and thus give constant conditions within the chamber. The specimen chamber is surrounded by an oil jacket, *J*, in which a thermometer, *T*, is suspended. The jacket oil may be brought to any desired temperature by means of a heating coil, or a side coil not shown in the diagram. The cover, *P*, of the jacket chamber

is provided with a scale which is marked in degrees or may be calibrated to read off directly, through the deflection of the pointer, *P*, the viscosity in terms of a standard liquid. The specimen chamber and the suspended cylinder are both made of copper to insure constant temperature throughout the specimen and the outside of the specimen chamber is provided with blades which keep the jacket

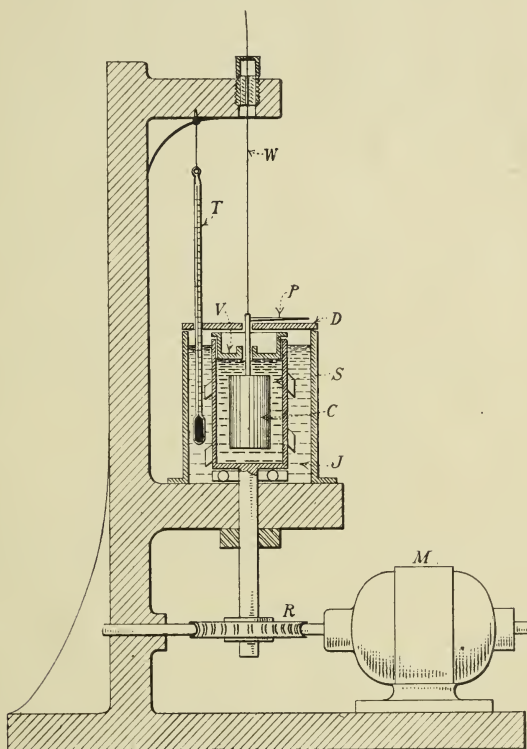


FIG. 4 THE NEW VISCOSIMETER

oil thoroughly mixed as the chamber revolves and thereby exposes the latter to a uniform temperature. This is an important factor toward insuring constant temperature throughout the specimen.

33 The experimental work has shown that the temperature of the specimen is uniform to within a small fraction of a degree. Moreover, the temperature of the specimen follows the temperature of the jacket oil so closely that the temperature-viscosity curve can be taken while the temperature is slowly raised or lowered. This

proves to be a great saving of time. It also saves labor, for one does not need to stand by the instrument continually. The deflection of the pointer is at any instant a measure of the viscosity, so all that is required is to take simultaneous readings of temperature and deflection at intervals during the heating or cooling process.

EXPERIMENTAL RESULTS

34 To test the accuracy of this viscosimeter, the temperature-viscosity curve was found for a light and a medium gas engine oil by the capillary tube method, the apparatus for which is shown in

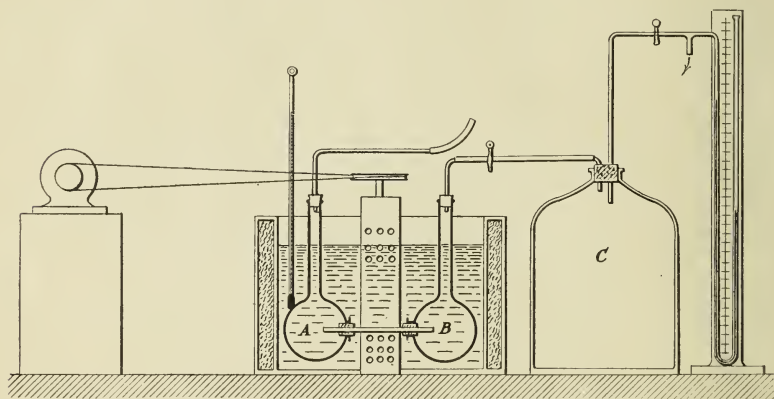


FIG. 5 CAPILLARY TUBE METHOD

Fig. 5. The oil was drawn from vessel A to vessel B, and vice versa, by connecting each in turn with the partial vacuum chamber, C. These vessels were submerged in a thermostat which could be maintained at any desired temperature. The results, in terms of the viscosity of water at 20 deg. cent., are given by the points enclosed in circles for curves 1 and 1a, Figs. 6 and 7, the latter referring to the lighter oil. The viscosity of these same oils as given by the new meter is represented on curves 1 and 1a by the points enclosed in squares. The agreement between the two methods is almost perfect.

35 The viscosity of these oils as given by a meter of the short capillary type, Fig. 2, is given in curves 2 and 2a. Curves 3 and 3a give the viscosity of these oils as obtained with a meter of the orifice form, Fig. 3. As predicted, the results given by the short capillary

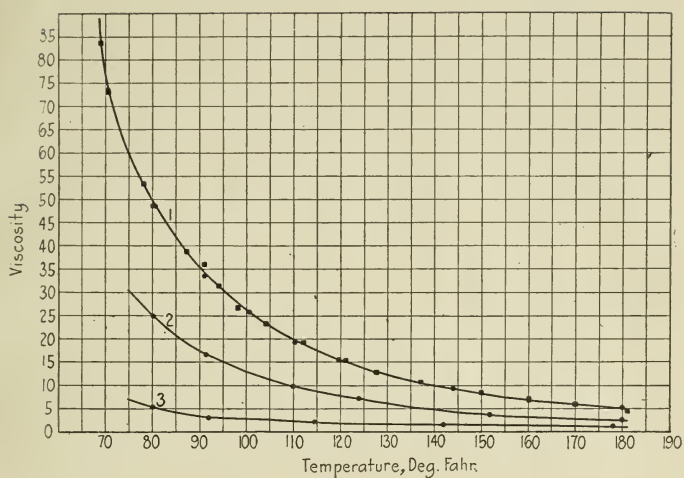


FIG. 6 VISCOSITY CURVES FOR MEDIUM GAS ENGINE OIL

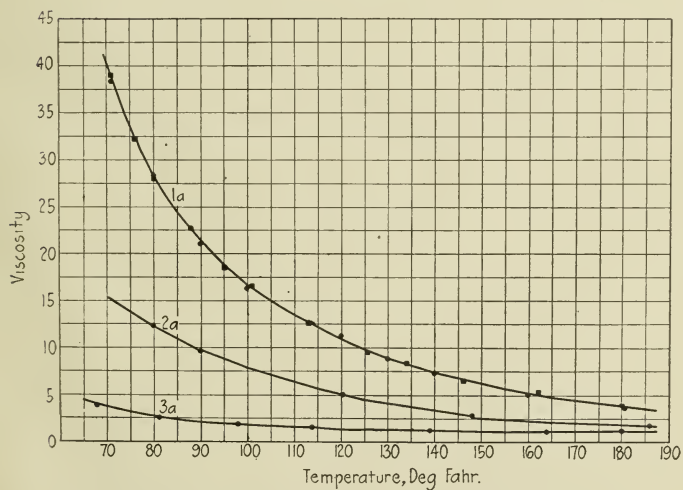


FIG. 7 VISCOSITY CURVES FOR LIGHT GAS ENGINE OIL

type are much too low (on the oils tested about 100 per cent too low) and the results given by the orifice type are still lower.

CONCLUSIONS

36 The errors inherent in all flow types of viscosimeters have been predicted and the predictions verified by experiment. The magnitude of the errors are such that these meters cannot be depended on for giving even approximate results. The various meters of this type on the market do not give results which are in agreement, and no one of these meters can justly be claimed as a standard.

37 The new viscosimeter of the non-flow type described has the following advantages:

- 1 It gives values for the viscosity which are in agreement with those given by the standard capillary tube method.
- 2 During a series of tests at various temperatures, the oil is not handled.
- 3 The sensitiveness of the instrument can be made anything desired by changing the speed of rotation of the specimen or by using suspension wires of various diameters.
- 4 The density or change in density is not a factor in computing the results, in fact the instrument may be graduated to read off the viscosity directly.
- 5 The viscosity of liquids which contain particles in suspension can be measured, and the operation of the meter is independent of the color of the specimen.
- 6 The temperature-viscosity curve can be taken with a fair degree of accuracy while the temperature is rising or falling, as the temperature of the specimen follows the temperature of the jacket so closely.
- 7 The personal error which arises in determining time intervals with a stop watch is removed.
- 8 The instrument is simple, rigid and self-contained. It has no separate parts to get lost or glass parts to get broken.

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